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ABSTRACT

Presented are exercises intended to supplement course work in air pollution control, specifically as they relate to combustion. Chapters offered in this workbook include: (1) Combustion Calculations, (2) Combustion System Design Problems, (3) Emission Calculations I, (4) Emission Calculations II, (5) Afterburner Design Problems, and (6) Combustion System Calculations. Each exercise presents the problem, factors to be computed, and the solution to the problem. (RE)

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# APTI
# Course 427
# Combustion Evaluation

# Student Workbook

U S DEPARTMENT OF HEALTH,
EDUCATION & WELFARE
NATIONAL INSTITUTE OF
EDUCATION

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# CHAPTER I

## COMBUSTION CALCULATIONS

PROBLEM I.1: Combustion of No. 6 Fuel Oil

Assume perfect combustion of No. 6 fuel oil with stoichiometric air. The gravimetric analysis of a sample of this fuel oil is:

| | |
|---|---|
| 88.52% | carbon |
| 10.87% | hydrogen |
| 0.40% | sulfur |
| 0.10% | nitrogen |
| 0.06% | oxygen |
| 0.05% | ash |

Compute:

1. The gravimetric analysis (weight percent) of the flue gases
2. Total volume of flue gases (at 500°F and 1 atmosphere) per pound of oil burned
3. Volume percent of $CO_2$ in dry flue gases

Solution to Problem I.1:

Select as a basis for calculation: 100 lbs. of fuel oil burned. This is chosen for convenience as the gravimetric analysis will give the amounts of various elements directly. Answers can easily be scaled to the 1 lb. of oil as required in Part 2.

A tabular form of solution is presented on the next page, as this will (i) help to organize thinking, (ii) permit presentation of results in a compact format, and (iii) avoid confusion

TABLE I.1

| FUEL | | | | COMB. AIR REQ'D | | FLUE PRODUCTS | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Element | M.W. | Quantity | | $O_2$ | $N_2$ | Cmpd. | M.W. | | | |
| | | lb. | lb-mole | lb-mole | lb-mole | | | lb-mole | lb. | wgt % |
| (a) | (b) | (c) | (d) | (e) | (f) | (g) | (h) | (i) | (j) | (k) |
| C | 12 | 88.52 | 7.38 | 7.38 | 27.8 | $CO_2$ | 44 | 7.38 | 325 | 21.8 |
| $H_2$ | 2 | 10.87 | 5.44 | 2.72 | 10.2 | $H_2O$ | 18 | 5.44 | 97.9 | 6.6 |
| S | 32 | 0.40 | 0.012 | 0.012 | 0.045 | $SO_2$ | 64 | 0.012 | 0.77 | 0.05 |
| $O_2$ | 32 | 0.06 | 0.002 | -0.002 | -0.007 | $O_2$ | 32 | - | - | - |
| $N_2$ | 28 | 0.10 | 0.0036 | - | - | $N_2$ | 28 | 38.0 | 1064 | 71.5 |
| Ash | - | 0.05 | - | | | | | | | |
| Total | | 100.00 | | 10.11 | 38.04 | | | 50.8 | 1,488 | 99.95 |
| | | | | | 48.15 | | | | | |

Notes for Column Headings:

(c) From gravimetric analysis of fuel

(d) = (c) ÷ (b)

(e) From basic chemistry, i.e.:

$C + O_2 \rightarrow CO_2$

$H_2 + \frac{1}{2}O_2 \rightarrow H_2O$

$S + O_2 \rightarrow SO_2$

Oxygen in fuel reduces air requirements. Excess air, if any, is usually specified as % of theoretical and added to the total.

(f) = (0.79/0.21) x (e)

(g) Products corresponding to complete combustion of various oxidizable elements in the fuel

(i) Pound-moles of products from the amount of combustibles in (d). Note that oxygen present only if excess air added, and nitrogen is the total of (f), including any from excess air.

(j) = (h) x (i)

(k) = (j) x 100/Σ(j)

Part 1.

Gravimetric analysis of flue gases given by Column (k) of the table.

Part 2.

Ideal gas law used to calculate the volume of flue gases (Equation 2.6, p. 2-8 of the Student Manual).

$$V = nRT/p$$

where $$n = \frac{50.8 \text{ lb-moles flue gases}}{100 \text{ lb oil}} = 0.508 \text{ lb-moles/lb}$$

from Table I.1

$R = 0.7302 \text{ atm-ft}^3/(\text{lb-mole } ^\circ\text{R})$

from Attachment 2-2, p. 2-24 of the Student Manual

$T = 500^\circ\text{F} + 460 = 960^\circ\text{R}$

$p = 1.0 \text{ atm.}$

$$V = (0.508)\ (0.7302)\ (906)/(1.0) = \underline{\underline{356 \text{ ft}^3}}$$

Part 3.

Dry flue gases (from Table I.1)

| Compound | lb-moles |
|---|---|
| $CO_2$ | 7.38 |
| $SO_2$ | 0.012 |
| $O_2$ | - |
| $N_2$ | 38.0 |
| Total | 45.4 lb-moles |

Vol. % $CO_2$ = 7.38 x 100 / 45.4 = $\underline{\underline{16.3 \%}}$

PROBLEM I.2: Combustion of Gases

Consider a gaseous fuel composed of 60% $H_2$ and 40% $CH_4$ by volume.

Determine:

1. The volume of air required for complete combustion of 1,000 scfm of the above gases with 100% theoretical air
2. The pounds of air required for burning 1.00 pounds of fuel
3. The volumetric analysis of flue gases (products), including water vapor (assume no water is condensed)
4. The gravimetric analysis of the reactants (fuel gas and air mixture)
5. The partial pressure of the water vapor in the flue for a total pressure of 14.7 psia

Solution to Problem I.2:

Complete and balance the combustion equation using 1 lb-mole of gas as the basis.

$$0.60\ H_2 + 0.40\ CH_4 + a\ O_2 + b\ N_2 \rightarrow c\ CO_2 + d\ H_2O + b\ N_2 \qquad (A)$$

To balance the equation

$c$ = _____

$d = 0.60 + 2\ (0.40)$ = _____

$a = c + d/2$ = _____

$b = (0.79/0.21)\ a$ = _____

Thus:

$$0.60\ H_2 + 0.40\ CH_4 + ___\ O_2 + \underline{4.14}\ N_2 \rightarrow ___\ CO_2 + ___\ H_2O + ___\ N_2 \qquad (B)$$

Rel. Volumes: $0.60 + 0.40 + \quad + 4.14 \rightarrow \quad + \quad + 4.14$ (C)

1.00 5.25

Rel. Mass: $1.20 + 6.40 + \underline{\quad} + 115.9 \rightarrow \underline{\quad} + \underline{\quad} + 115.9$ (D)

7.60

$\underline{\quad}$

Part 1.

From Equation (C) note that 5.24 volumes of air required for complete combustion of 1.00 volumes of this fuel gas.

Therefore:

Vol. of air = (5.24 scfm air/scfm gas) (_____ scfm gas) = _____ scfm air

Another approach makes use of Equation 2.4, p. 2-7 of the Student Manual, which for gases containing only $H_2$ and $CH_4$ reduces to:

$$V_{A,\,t} = 2.38\,(H_2) + 9.53\,(CH_4) \qquad \text{(E)}$$

where $(H_2) = 0.60$

$(CH_4) = 0.40$

$V_{A,\,t}$ = 2.38 (_____) + 9.53 (_____) = 5.24 scf air/ scf gas

which is the same as obtained in the Preliminary Calculation (Equation C above).

Part 2.

From Equation D above, 7.60 lb. of fuel gas requires _____ lb. air.

Air required per pound of gas burned = (_____ lb. air)/7.60 lb. gas

= _____ lb. air/lb. gas

Part 3.

From Equation (C) above, total volume of flue products is:

_____ + _____ + 4.14 = _____ (F)

$CO_2$ $H_2O$ $N_2$

Volume % of flue products:

% $CO_2$ = _____ x 100 / (Result of Equation F above) = _____ %

% $H_2O$ = _____ x 100 / (_____) = _____ %

% $N_2$ = 4.14 x 100 / (_____) = _____ %

Part 4.

Tabulate the left-hand side of Equation (B) above:

| Reactant | Relative Mass | Wgt. % |
|---|---|---|
| $H_2$ | 1.20 | _____ |
| $CH_4$ | 6.40 | _____ |
| $O_2$ | _____ | _____ |
| $N_2$ | 115.9 | _____ |
| Total | _____ | 100.0 |

Note: Wgt. % of Reactant i = (Mass of i) x 100 / Total Mass

Part 5.

Partial pressure of a gaseous component is given by Equation 2.9, p. 2-10 of the Student Manual.

$$P_{H_2O} = (n_{H_2O}) * (p)/n_{total} \quad (G)$$

where n = lb-moles or volume from Equation (C)

p = total pressure of flue products

Thus:

$P_{H_2O}$ = (_____ lb-moles $H_2O$) (14.7 psia) / (_____ lb-moles of flue gases)

$P_{H_2O}$ = _____ psia

PROBLEM I.3: Available Heat

Consider a boiler which burns 10,000 standard cubic feet per hour of a waste gas with higher heating value of 258 Btu/scf.

Determine:

1. The gross heating value per hour for complete combustion
2. The available heat if the flue gases leave the boiler heat exchanger at 500°F and complete combustion is achieved with theoretical combustion air
3. The available heat from the same boiler if 20% excess air had been used and flue gas exit temperature was still 500°F

Solution to Problem I.3:

Part 1.

Gross heating value per hour = ($Q_H$, Btu/scf) (Fuel rate, scf/hr) (A)

= (258 Btu/scf) (10,000 scf/hr)

= 2,580,000 Btu/hr

Part 2.

Use Attachment 2-9, p. 2-31 of the Student Manual to estimate the available heat, $Q_A$, from the above fuel with flue gases at 500°F.

Interpolate between curves in Attachment 2-9 at identical flue gas temperatures using the following ratio:

$$\left[\frac{Q_A}{Q_H}\right]_{\text{Desired fuel}} = \left[\frac{Q_A}{Q_H}\right]_{\text{Reference fuel}} \quad \text{(B)}$$

Choosing Producer Gas as the reference fuel:

$$(Q_A/Q_H)_{\text{Ref. fuel, } 500^\circ F} = (130/163) = 0.80$$

With waste gas: $Q_H$ = 258 Btu/scf, from Equation (B) above:

$$Q_A = (258 \text{ Btu/scf})\ (0.80) = 206 \text{ Btu/scf}$$

Total heat available from waste gases = (10,000 scfh) (206 Btu/scf)

= 2,060,000 Btu/hr

Part 3.

Attachment 2-10, p. 2-32 of the Student Manual, gives available heat as the percent gross heating value with various amounts of excess air.

With flue gases at 500°F and 20% excess air, read

$$(Q_A/Q_H) \times 100 = 79\% \qquad \text{(C)}$$

Thus, heat available per hour with 20% excess air is:

$$Q_A = (79/100)\ (2{,}580{,}000 \text{ Btu/hr}) = 2{,}038{,}000 \text{ Btu/hr}$$

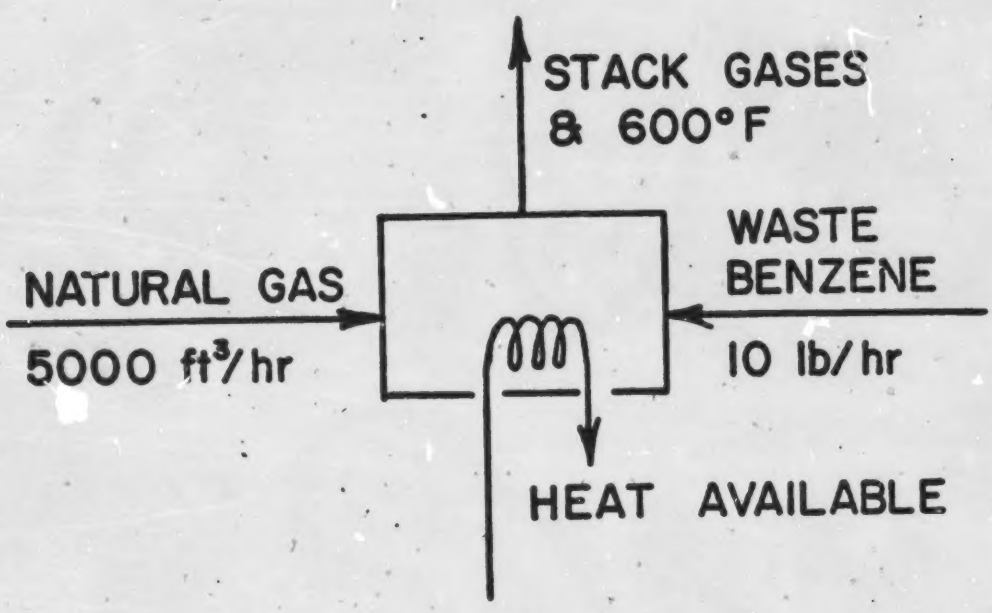
PROBLEM I.4: Liquid Waste Combustion in Natural Gas-Fired Boiler

Combustible liquid waste from a manufacturing process is to be burned in a boiler which is fired with 1,059 Btu/scf higher heating value natural gas at a rate of 5,000 scfh. The liquid waste is equivalent to 10 lb/h of benzene.

Determine:

1. The total gross heating value to the boiler per hour.
2. The amount of combustion air required to burn the waste liquid. Assume a 20% excess of theoretical air and express your results in scfm.
3. The amount of available heat from the boiler if the flue gases leave the heat exchanger at 600°F and complete combustion is achieved with 20% excess air.

Flow Diagram



Solution to Problem I.4:

Choose as a basis:

1 hour of operation.

Part 1.

Gross heating value of natural gas: $Q_{H,\ gas}$ = 1,059 Btu/scf.

Gross heating value of benzene is obtained from Attachment 2-1, p. 2-23 of the Student Manual:

$Q_{H,\ benzene}$ = _____ Btu/lb

Total gross heat input to the boiler is:

Natural gas (5,000 scfh) (1,059 Btu/scf) = _____ Btu/hr

Benzene (10 lb/hr) (_____ Btu/lb) = _____ Btu/hr

Total = _____ Btu/hr

Part 2.

Attachment 2-1, p. 2-23 of the Student Manual, gives the combustion air requirement for benzene (Substance No. 21) as _____ lb air/lb benzene or _____ scf air/scf benzene.

Density of benzene; $\rho_{benzene}$ is _____ lb/scf.

Theoretical air required to burn benzene type waste completely

$$V_{A,\ t} = (\dot{m}_{benzene}/\rho_{benzene})\ \text{(Theoretical scf air/scf benzene)}$$

$$V_{A,\ t} = \frac{10\ \text{lb/hr}}{(_____\ \text{lb/scf benzene})} \times _____\ \text{scf air/scf benzene)}$$

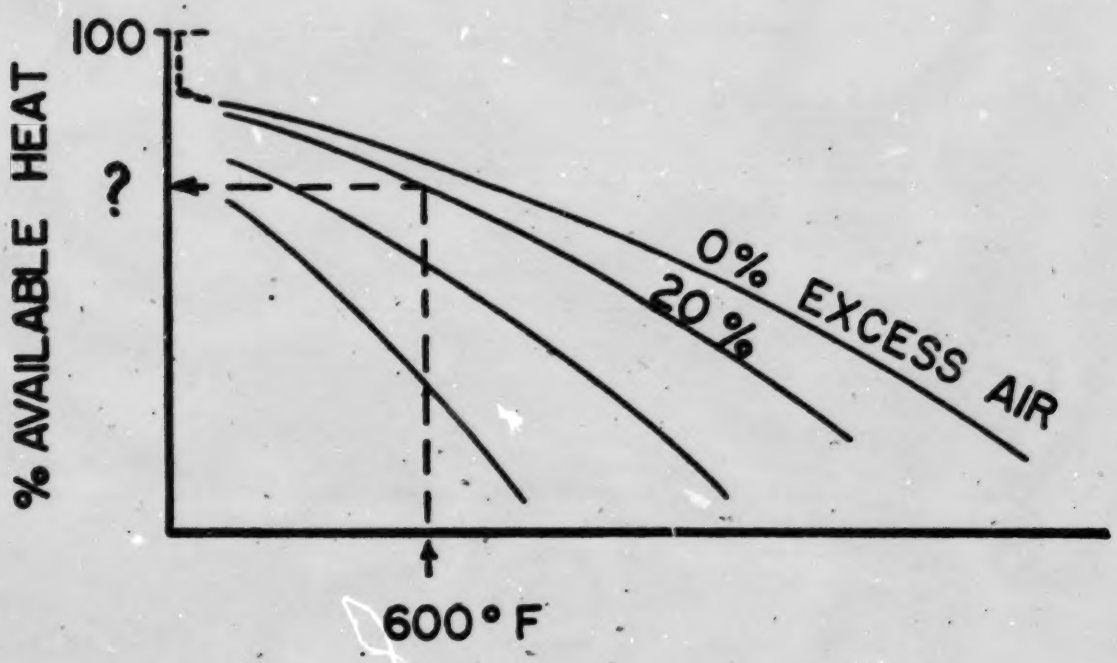
$$= _____\ \text{scf air/hr}$$

Air requirements with 20% excess air:

$V_{air}$ = (1.20) (_____ scf air/hr) = _____ scf air/hr

Part 3.

Refer to Attachment 2-10, p. 2-32 of the Student Manual. Read available heat as percent of gross heating value with flue gases at 600°F and 20% excess air as _____ %




Heat available from the boiler

= ( _____ Btu/hr) ( ____ %/100) = _____ Btu/hr

[from Part 1] [from Attachment 2-10]

PROBLEM I.5: Combustion Calculations with Heat Recovery

Part A

A chemical plant has installed an industrial boiler to produce process steam. The boiler is fired with natural gas of the following composition by volume: 90% methane, 5% ethane, and 5% nitrogen. The boiler is designed to burn 80,000 cubic feet per hour (delivered at 60°F) of natural gas at 10% excess combustion air.

Determine:

1. The gross heat input to the boiler, Btu per hour. Assumptions: (a) natural gas and combustion air enter the boiler at 60°F; (b) heat losses from the boiler due to radiation and convection are negligible.

2. The combustion air requirement, cubic feet per hour (at 60°F, 30 inches mercury pressure). Assume average atmospheric conditions are 60°F and 30 inches mercury pressure.

3. The available heat for process steam if the flue gases leave the boiler heat exchanger at 400°F.

Part B

The personnel of the chemical plant are now considering the addition of an air preheater to the boiler to preheat combustion air. Calculations show that the flue gases leaving the heat exchanger section would enter the air preheater at the following conditions: 1,500,000 cubic feet per hour at 400°F. The air preheater will be designed to reduce the flue gas temperature to 250°F. At conditions of complete combustion, calculations show the flue gases entering the air preheater to be of the following composition by volume: 8.8% $CO_2$, 1.7% $O_2$, 72.3% $N_2$, and 17.2% $H_2O$. (Note: Calculations show the water vapor flow rate in the flue gases equals 7,400 lbs. per hour.)

Determine:

4. The heat recovered (H.R.) from the flue gases by the air preheater based on the flue gas analysis and flue gas flow rate. (Note: Use Equation 1 shown below.)

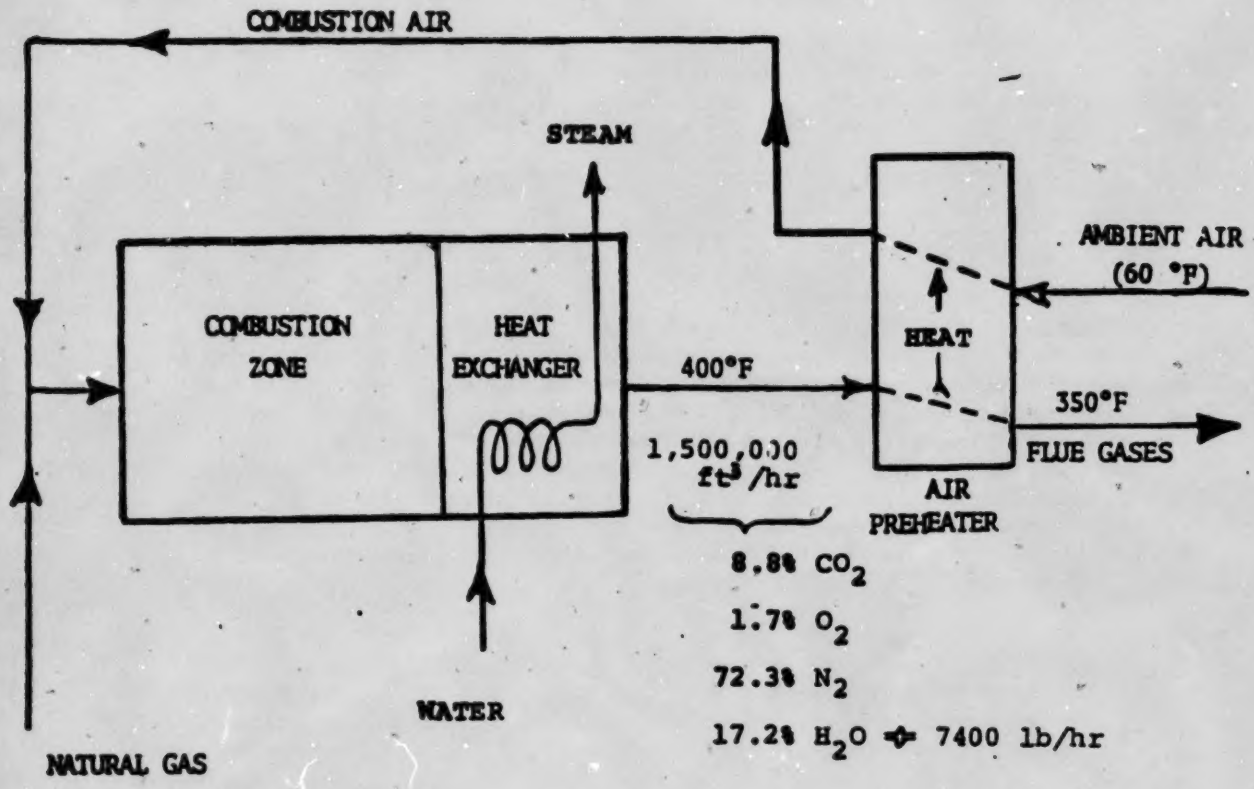
5. The increase in combustion air temperature resulting from the use of an air preheater. (Note: Use Equation 2 shown below.)

6. The combustion air temperature after passing through the air preheater.

$$H.R. = \sum \left(\text{flow rate of each component}\right) \times \left(\text{difference in heat content of each}\right) \quad (1)$$

$$H.R._{Air} = 0.24 \frac{Btu}{lb\ ^{\circ}F} \times \text{temperature increase} \times \text{air flow rate} \quad (2)$$

LOW DIAGRAM FOR BOILER:



**Solution to Problem I.5:**

**Basis:** 1 hour of operation

**Part 1.**

| Substance | | Volumetric Flow Rate scfh | (a) Gross Htg. Value, Btu/scf | (b) Heat Input Btu/hr |
|---|---|---|---|---|
| Methane — $CH_4$ | (0.90)(80,000) = | _____ ; | _____ | _____ |
| Ethane — $C_2H_6$ | (0.05)(80,000) = | _____ ; | _____ | _____ |
| Nitrogen — $N_2$ | (0.05)(80,000) = | _____ ; | 0 | 0 |
| | Totals: | _____ scfh | | _____ Btu/hr |

Note: (a) From Attachment 2-1, p. 2-23 of the Student Manual.

(b) Obtained by multiplying volumetric flow rate by the corresponding gross heating value.

**Part 2.**

Combustion air requirements:

| Combustible Substance | Volume, scfh | Theor. Air* scf air/scf gas | Actual Air (10% excess) scf air/scf | scf air/hr |
|---|---|---|---|---|
| $CH_4$ | 72,000 | _____ | _____ | _____ |
| $C_2H_6$ | 4,000 | _____ | _____ | _____ |
| | | Total Air = | | _____ scfh |

*From Attachment 2-1, p. 2-23 of the Student Manual.

Part 3.

For available heat as percent of gross heating value, use Attachment 2-10, p. 2-32 of the Student Manual.

Read for 400°F flue gases and 10% excess air _____ %.

Available heat from the boiler = (_____ gross Btu/hr)(____ % gross/100)

= _____ Btu/hr.

Part 4.

Need to calculate flow rate of combustion products in lb/hr. First correct flue gas flow rate from 400°F to standard temperature of 60°F, using Charles' law (Equation 2.7, p. 2-9 of the Student Manual).

$$V_{flue,\ 60^\circ F} = (1{,}500{,}000\ ft^3/hr)\ (460 + ____^\circ F) / (460 + ____^\circ F)$$

$$= _____\ ft^3/hr$$

Mass flow rate of component = (volume fraction) (total volume flow) (density)

| Component | Fraction | Density lb/ft$^3$ | Mass Flow lb/hr | Enthalpy, Btu/lb | | | |
|---|---|---|---|---|---|---|---|
| | | | | at 400°F | | at 350°F | |
| | | | | Btu/lb | Btu/hr | Btu/lb | Btu/hr |
| $CO_2$ | | | | | | | |
| $O_2$ | | | | | | | |
| $N_2$ | | | | | | | |
| $H_2O$ | | | 7,400 | 1,212 | 8.97 x $10^6$ | | |
| Total | 1.00 | | | $H_{400}$ = | | $H_{350}$ = | |

Note: Densities available from Attachment 2-1, p. 2-23 of the Student Manual. Enthalpies from Attachment 2-7, p. 2-29 of the Student Manual.

Heat recovered from cooling flue gases = $(H_{400} - H_{350})$ Btu/hr.

$H.R._{Air} = \Delta H_{Flue\ Gases}$ = _____ - _____ = _____ Btu/hr

Part 5.

Refer to Equation (2) of the Problem Statement, which on rearrangement gives:

$$\Delta T_{Air} = (H.R._{Air}) / (0.24 \text{ Btu lb}^{\circ}\text{F} \times \text{Air Flow Rate, lb/hr})$$

Obtain density of air from Attachment 2-1, p. 2-23 of the Student Manual, to compute:

Air Flow Rate, lb/hr = (Volumetric Air Flow, scfh)(density, lb/scf)

= ( _____ scfh)( _____ lb/scf)

= _____ lb/hr.

Do Not Film This Page

Substituting into expression for $\Delta T_{Air}$ :

$$\Delta T_{Air} = \frac{(\text{_____ Btu/hr})}{(0.24 \text{ Btu/lb-}^{\circ}\text{F})(\text{_____ lb/hr})} = \text{_____}\ ^{\circ}\text{F}$$

Part 6.

Air temperature after preheater = $60^{\circ}F + \Delta T_{Air}$

= 60 + _____ = _____ $^{\circ}F$

CHAPTER II

COMBUSTION SYSTEM DESIGN PROBLEMS

PROBLEM II.1: Calculation of Furnace Volume

Consider the design of a pulverized coal-fired furnace which operates with an average energy release rate of 25,000 Btu/hr per cubic foot of furnace volume. The furnace produces steam with an energy output of $55 \times 10^6$ Btu/hr and a thermal efficiency of 80%.

Calculate:

1. The furnace volume for the steam generator.

Solution for Problem II.1:

1. Determine the fuel energy input required in order to realize the given energy output

$$Q_H = \frac{Q_s}{\eta} = \frac{55 \times 10^6 \text{ Btu/hr}}{0.80}$$

$$= _____ \text{ Btu/hr}$$

2. Refer to Table 9.6 in the Student Manual, p. 9-10, to obtain the average design value for the heat release rate of 25,000 Btu/hr $ft^3$ for pulverized coal firing.

$$\text{Furnace Volume} = \frac{Q_H}{25{,}000 \frac{\text{Btu}}{\text{hr ft}^3}} = \frac{(\quad)}{25{,}000 \frac{\text{Btu}}{\text{hr ft}^3}}$$

$$= _____ \text{ ft}^3$$

PROBLEM II.2: Furnace Volume Plan Review

An industrial organization proposes to build a 100,000 pounds-per-hour steam generator. The furnace is to be fired by a chain-grate stoker with continuous ash removal, similar to that shown in Attachment 9-4 of the Student Manual, p. 9-19. The furnace is 12 ft. wide (across the front), 14 ft. deep, and 28 ft. high. The volume corresponding to these dimensions includes the superheater volume, which is small enough to be neglected in the calculation. The fuel for the proposed unit is to be the high-volatile bituminous coal described in Attachment 3-11 of the Student Manual, p. 3-20. The steam generator will require 6 tons per hour of this coal to achieve its full steam capacity.

Determine:

1. If the furnace volume is adequate.

Solution for Problem II.2:

1. Calculate the furnace volume using the dimensions given:

   Furnace volume = (length) x (width) x (height) - (superheater volume)

   = (  ) x (  ) x (  ) - ( 0.0)

   = _____ $ft^3$

2. Calculate the energy release rate per cubic foot for the specified fuel and design capacity.

   $$\text{Energy release rate} = \frac{(\text{coal firing rate}) \times (\text{higher heating value})}{(\text{Furnace volume})}$$

   $$= \frac{(\qquad) \times (\qquad)}{(\qquad)}$$

   = _____ Btu/hr $ft^3$

3. Compare the value obtained above to that given in Table 9.6 on p. 9-10 of the Student Manual.

PROBLEM II.3: Calculation of Furnace Gas Exit Temperature

A reheat steam generator design has energy utilization based on the total energy input (higher heat value) as follows:

| | | |
|---|---|---|
| 1. | Energy absorbed in radiant boiler . . . . . | 49.5% |
| 2. | Energy absorbed in convection superheater . . . . . | 20.8% |
| 3. | Energy absorbed in economizer . . . . . | 6.6% |
| 4. | Energy absorbed in steam reheater . . . . . | 8.0% |
| 5. | Energy absorbed in air preheater . . . . . | 5.0% |
| 6. | Furnace heat losses . . . . . | 3.0% |
| 7. | Flue gas and other losses . . . . . | 7.1% |
| | | 100.0% |

The unit is fired with pulverized coal, using the coal described as the "as received" coal listed in Attachment 3-12 on p. 3-21 of the Student Manual. The unit operates with 15% excess air; and the combustion air is preheated to 300°F.

Calculate:

1. The temperature of the gas leaving the furnace.

Solution for Problem II.3:

1. Determine the theoretical air required to burn the coal specified, using Equation 4.1 on p. 4.4 of the Student Manual. The coal is 75% carbon, 5% hydrogen, 2.3% sulfur, 1.5% nitrogen, 6.7% oxygen, 2.5% moisture, and 7.0% ash.

$$\text{Theoretical Air} = A_t = 11.53\,(C) + 34.34\,(H_2 - \frac{O_2}{8}) + 4.29\,(S)$$

$$= 11.53\,(\ \ ) + 34.34\,(\ \ - \frac{\ \ }{8}) + 4.29\,(\ \ )$$

$$= \underline{\qquad\qquad} \text{ lbs per lb of coal}$$

2. Calculate total air.

Total Air = $A_a$ = $(1.0 + \frac{\% EA}{100}) A_t$

$(1.0 + \frac{\quad}{100})$ x ( )

_____ lbs per lb of coal.

3. Estimate the amount of flue gas produced using Equation 4.2 on p. 4-5 of the Student Manual:

Theoretical flue gas = G

= ($m_f$ - noncombustibles) + $m_f A_t$

Choose a basis of one pound of fuel, so that $m_f$ = 1:

G = $(1.0 - \frac{\% Ash}{100}) + (1.0)$ x $A_t$

= $(1.0 - \frac{\quad}{100})$ + 1.0 x ( )

= _____ lb gas per lb of coal

Actual flue gas = $G_f$ = (G + $A_f$) = G + $\frac{\% EA}{100}$ x $A_t$

= ( ) + $(\frac{\quad}{100})$ x ( )

= _____ lbs gas per lb of coal

4. Calculate the useful energy, $Q_u$, absorbed in the furnace region (radiant boiler in this case).

$Q_u$ = (fraction of energy absorbed in radiant boiler) x (HHV)

= 0.495 x ( )

= _____ Btu/lb of coal

5. Note that $Q_u$ is also related to the energy input as follows:

$Q_u$ = (lower heating value) - (losses) - (energy in the gases leaving furnace)

which is given by Equation 4.8 on p. 4-7 of the Student Manual.

$$Q_u = H - Q_L - G_f C_p (t_f - t_a)$$

a. The energy, H, is obtained from

H = HHV - energy of the water in flue gas

= HHV - $Q_v$,

where:

water in flue gas = 9.0 x ($H_2$ in fuel) + (as-fired moisture)

= 9.0 x ( ) + ( )

= _____ lbs $H_2O$/lb coal

and the energy in this water is

$Q_v$ = (lbs of water per lb fuel) x (latent heat of vaporization)

= ( ) $\frac{\text{lbs } H_2O}{\text{lbs fuel}}$ x (1,000 $\frac{\text{Btu}}{\text{lb}}$)

= _____ Btu per lb coal

now

H = HHV - $Q_v$

= ( ) - ( )

= _____ Btu per lb of coal

b. The losses, $Q_L$, are:

$Q_L$ = fraction of energy lost from furnace x (HHV)

= ( ) x ( )

= _____ Btu per lb of coal

c. The furnace gas temperature is calculated by substituting values obtained from $Q_u$, H, $Q_L$, $G_f$ together with a value for $C_p$ = 0.26 Btu/lb $^{o}F$ and $t_a$ = 300$^{o}F$:

$$Q_u = H - Q_L - G_f C_p (t_f - t_a)$$

( ) = ( ) - ( )

$$- ( ) \left(0.26 \frac{\text{Btu}}{\text{lb } ^{o}F}\right) (t_f - 300)$$

therefore:

$t_f$ = _____ $^{o}F$

# CHAPTER III

## EMISSION CALCULATIONS I

PROBLEM III.1: Pollutant Emissions from Coal-Fired Power Plant

Plans call for a 500 $MW_e$ power plant to have a dry-bottom design and to burn pulverized coal. The overall thermal efficiency is designed to be 34%. The coal specified in the plans contains 1.3% sulfur, 22% ash, and has a 12,500 Btu/lb HHV.

Compute:

1. The input energy required when the unit is operated at the rated capacity.
2. The coal firing rate at the rated capacity.
3. The pollutant mass rate for emissions of:
   a. $SO_2$
   b. Particulates
   c. $NO_x$
   d. HC
   e. CO
4. The process emissions per million Btu of energy input for
   a. $SO_2$
   b. Particulates
5. The degree of control required to meet a 1.2 lb $SO_2/10^6$ Btu performance standard for $SO_2$.
6. The degree of control required to meet a 0.1 lb particulate/$10^6$ Btu performance standard for particulates.

**Solution to Problem III.1:**

1. Plant electric output rating and thermal efficiency can be used to find energy input from Equation 4.9, on p. 4-8 of the Student Manual.

$$Q_E = \text{energy in} = \frac{\text{energy out}}{\text{thermal eff}} = \frac{Q_s}{\eta}$$

$$= \frac{(\quad)\ MW_e}{(\quad)} \times 3413 \times 10^3 \ \frac{Btu}{MW_e\ hr}$$

$$= _____ \ \frac{Btu}{hr}$$

2. With the value of $Q_E$ and the coal HHV, the coal-firing rate is given by:

$$\dot{m}_f = \text{coal fired}, \frac{Ton}{hr} = \frac{Q_E}{\text{HHV per ton}} = \frac{(\quad)\ \frac{Btu}{hr}}{(\quad)\ \frac{Btu}{lb} \times 2{,}000\ \frac{lb}{ton}}$$

$$= _____ \ \frac{Ton}{hr}$$

3a. The pollutant mass rate for $SO_2$ can be obtained using the coal-firing rate and the emission factor for $SO_2$ (refer to Student Manual, p. 5-30 for emission factors)

$$(PMR)_{SO_2} = 38 \times S\ \frac{lb\ SO_2}{ton\ coal} \times \dot{m}_f\ \frac{ton\ coal}{hr}$$

$$= 38 \times (\quad)\ \frac{lb\ SO_2}{ton\ coal} \times (\quad)\ \frac{ton\ coal}{hr}$$

$$= _____ \ lb\ SO_2/hr$$

b. $(PMR)_{part.} = 17 \times A \frac{\text{lb part.}}{\text{ton coal}} \times m_f \frac{\text{ton coal}}{\text{hr}}$

$= 17 \times (\quad) \frac{\text{lb part.}}{\text{ton coal}} \times (\quad) \frac{\text{ton coal}}{\text{hr}}$

$=$ _____ lb part./hr

c. Similarly, the PMR for $NO_X$ would be

$(PMR)_{NO_X} = 18 \frac{\text{lb } NO_X}{\text{ton coal}} \times m_f \frac{\text{ton coal}}{\text{hr}}$

$= 18 \frac{\text{lb } NO_X}{\text{ton coal}} \times (\quad) \frac{\text{ton coal}}{\text{hr}}$

$=$ _____ lb $NO_X$/hr

Similarly the PMR's for CO and HC are:

d. $(PMR)_{HC} = (\quad) \frac{\text{lb HC}}{\text{ton coal}} \times m_f \frac{\text{ton coal}}{\text{hr}}$

$= (\quad) \times (\quad)$ lb HC/hr

$=$ _____ lb HC/hr

e. $(PMR)_{CO} = (\quad) \frac{\text{lb CO}}{\text{ton coal}} \times m_f \frac{\text{ton coal}}{\text{hr}}$

$= (\quad) \times (\quad)$ lb CO/hr

$=$ _____ lb CO/hr

4a. The $SO_2$ process emissions per million Btu energy input will be computed from the $SO_2$ pollutant mass rate and the input energy rate:

$$E_{SO_2} = \frac{(PMR)_{SO_2}}{Q_H}$$

$$= \frac{(\quad)\ \frac{lb\ SO_2}{hr}}{(\quad)\ \frac{Btu}{hr}}$$

$$= \frac{\qquad\qquad}{}\ \frac{lb\ SO_2}{10^6\ Btu}$$

b. The particulate emissions per million Btu energy input will be computed similarly:

$$E_{part} = \frac{(PMR)_{part}}{Q_H}$$

$$= \frac{(\quad)\ lb\ particulates/hr}{(\quad)\ Btu/hr}$$

$$= \frac{\qquad\qquad}{}\ \frac{lbs_{part}}{10^6\ Btu}$$

5. The computations presented above can be used to compute the degree of control required to meet a given emission standard. For this problem the performance standards are listed on p. 5-20 in the Student Manual. For a solid-fuel-fired power plant which is 250 x $10^6$ Btu/hr or larger, the $SO_2$ standard is 1.2 lb $SO_2/10^6$ Btu.

From above the calculated $E_{SO_2}$ = _____ lb $SO_2/10^6$ Btu

Therefore,

$$\text{Degree of control needed} = \frac{E_{SO_2} - \text{Standard}}{E_{SO_2}} \times 100\%$$

$$= \frac{(\qquad) - 1.2}{(\qquad)} \times 100\%$$

$$= \underline{\qquad\qquad}\ \%\ \text{reduction of the uncontrolled value}$$

6. Similarly the particulates standard is 0.1 lb/$10^6$ Btu and the estimated uncontrolled particulates was

$$E_{part} = (\qquad) \frac{\text{lb particulates}}{10^6\ \text{Btu}}$$

$$\text{Degree of control needed} = \frac{E_{part} - \text{Standard}}{E_{part}} \times 100\%$$

$$= \frac{(\qquad) - .1}{(\qquad)} \times 100\%$$

$$= \underline{\qquad\qquad}\ \%\ \text{reduction of the uncontrolled value}$$

PROBLEM III.2: Fuel Sulfur Limit Calculation

A 22-degree API fuel oil is to be burned subject to a maximum $SO_2$ emission standard of 0.8 lb $SO_2/10^6$ Btu input.

Determine:

1. The maximum sulfur composition of the 22-degree API fuel oil which meets the standard without flue gas desulfurization.

Solution to Problem III.2:

From Student Manual, Attachment 3-5, p. 3-15, find:

total heat of combustion at constant volume = _____ $Btu/lb_m$

One should note that $SO_2$ is 1/2 oxygen and 1/2 sulfur by weight.

Therefore,

$$\text{Max S} = \frac{.5 \text{ lb S}}{\text{lb } SO_2} \times \frac{(0.8 \text{ lb}_m \ SO_2)}{10^6 \text{ Btu}} \times \frac{(\quad) \text{ Btu}}{\text{lb}_m \text{ oil}}$$

$$= _____ \frac{\text{lb}_m \text{ S}}{\text{lb}_m \text{ oil}}$$

= _____ % S in the oil

CHAPTER IV

EMISSION CALCULATIONS II

PROBLEM IV.1: Excess Air Calculation Based on Orsat Analysis

The effluent of a combustion unit is characterized by:

| | |
|---|---|
| Orsat Analysis: | 11% $CO_2$, 9% $O_2$, 2% CO |
| $SO_2$: | 120 ppm |
| Gas Flow: | 200,000 acfm @ 27.5 in.Hg pressure, 340°F temperature, 8% moisture by volume |
| Particulates: | 400 grain per acf |

Calculate:

1. The percentage of excess air in the flue gas using Equation 1 from Attachment 5-4, p. 5-23 of the student manual.
2. The $SO_2$ emissions in micrograms per cubic meter ($\mu g/m^3$).
3. The volume of the dry flue gas at the observed conditions.
4. The volume of the dry flue gas at standard conditions which are a pressure of 30.00 inches of mercury and a temperature of 60°F.
5. The particulate concentration based on standard pressure and temperature.
6. The particulate emission concentrations corrected for
   a. 50% excess air
   b. 12% $CO_2$
   c. 6% $O_2$

**Solution for Problem IV.1:**

1. Refer to Student Manual, p. 5-23, to obtain the equation for computing the excess air from an Orsat analysis.

$$EA = \frac{(O_{2p} - 0.5\ CO_p)}{0.264\ N_{2p} - (O_{2p} - 0.5\ CO_p)} \times 100\%$$

The nitrogen in the product gas, $N_{2p}$, may be calculated as follows:

$N_{2p}$ = 100 - $\%CO_2$ - $\%O_2$ - %CO

= 100 - (  ) - (  ) - (  )

= _____ % $N_2$

Substitute the above value into equation for EA:

$$EA = \frac{(\quad) - 0.5\ (\quad)}{0.264\ (\quad) - (\quad - 0.5\ (\quad))}$$

= _____ % excess air

2. Convert 120 $SO_2$ ppm to $\mu g/m^3$ using Equation 5.8 on p. 5-5 of the Student Manual:

1 ppm = 40.8 x (MW) $\frac{\mu g}{m^3}$

1 ppm $SO_2$ = 40.8 x (  ) $\frac{\mu g}{m^3}$ = _____ $\frac{\mu g}{m^3}$

120 ppm $SO_2$ = 120 x (  ) $\frac{\mu g}{m^3}$ = _____ $\frac{\mu g}{m^3}$

Reduce the $\frac{\mu g}{m^3}$ units to $\frac{mg}{m^3}$, by noting that

$$1{,}000 \times \frac{\mu g}{m^3} = 1 \frac{mg}{m^3}$$

Therefore

$$120 \text{ ppm } SO_2 = (\quad) \frac{\mu g}{m^3} \times 10^{-3} \frac{mg}{\mu g}$$

$$= _____ \frac{mg}{m^3}$$

3. Calculate the volume of the gas as follows:

$$V_{o\ dry} = V_{o\ wet} \text{ (1.0 - moisture)}$$

$$= (\quad) \text{ (1.0 - } \quad)$$

$$= _____ \text{ cfm}$$

4. Refer to the Student Manual, Equation (1) on p. 5-22 and reduce $V_{o\ dry}$ to $V_{s\ dry}$, using $P_s = 30.00$ Hg and $T_s = 520$ R

$$V_s = V_o \left[\frac{P_o}{P_s}\right]\left[\frac{T_s}{T_o}\right]$$

$$= (\quad) \times \frac{(\quad)}{(\quad)} \times \frac{(\quad)}{(\quad)}$$

$$= _____ \text{ scfm}$$

5. Likewise reduce the particulate loading concentration to that at the standard conditions

$$C_{vs} = C_{vo} \left[\frac{P_s}{P_o}\right]\left[\frac{T_o}{T_s}\right]$$

$$= (\quad) \times \frac{(\quad)}{(\quad)} \times \frac{(\quad)}{(\quad)}$$

$$= \underline{\qquad\qquad} \text{ grain/scf}$$

6a. Refer to the Student Manual, p. 5-23 and use Equations (2) and (3) to calculate the particulate concentrations on a 50% excess-air basis

$$F_{50V} = 1 - \left[\frac{1.50\ O_{2p} - 0.133\ N_{2p} - 0.75\ CO_p}{0.21}\right]$$

$$= 1 - \left[\frac{1.50\ (\quad) - 0.133\ (\quad) - 0.75\ (\quad)}{0.21}\right]$$

$$= \underline{\qquad\qquad}$$

$$C_{50V} = \frac{C_{vs}}{F_{50V}} = \frac{(\quad)}{(\quad)} = \underline{\qquad\qquad} \text{ grain/scf}$$

b. Correct to 12% $CO_2$, using Equations (6) and (7) on p. 5-23 of the Student Manual

$$F_{12V} = \frac{CO_{2p}}{0.12} = \frac{(\quad)}{(\quad)} = \underline{\qquad\qquad}$$

$$C_{12V} = \frac{C_{vs}}{F_{12V}} = \frac{(\quad)}{(\quad)} = \underline{\qquad\qquad} \text{ grain/scf}$$

c. Correct to 6% $O_2$ using Equations (10) and (11); however, note that Equation (10) should be modified for the net $O_2$ (after the CO is oxidized):

$$F_{6V} = \frac{0.21 - (O_{2p} - 0.5\ (CO_p))}{0.15}$$

$$= \frac{0.21 - (\qquad - 0.5\ (\qquad))}{0.15}$$

$$= _____$$

$$C_{6V} = \frac{C_{vs}}{F_{6V}} = \frac{(\qquad)}{(\qquad)} = _____ \text{ grain/scf}$$

PROBLEM IV.2: Use of F-factors to Compute Emission Concentrations

The effluent from a bituminous coal-fired source is found to have a particulate concentration, $C_{vs}$, equal to 2.0 grains/scf (dry basis). The flue gas oxygen is 9% and the carbon monoxide is 2%, as measured on a dry basis.

Calculate:

1. The particulate emissions in the units of (grains/million Btu) using the F-factor technique

Solution to Problem IV.2:

From Attachment 5-4, p. 5-25, of the Student Manual, find:

$$F_d = _____ \frac{\text{dscf}}{10^6 \text{ Btu}}$$

with the given $C_{vs}$ value and the computed $F_d$, use Equation (5.32), p. 5-16, to calculate E, the particulate emissions, grains/$10^6$ Btu

$$E = C_{vs} F_d \left[\frac{20.9}{20.9 - (O_{2p} - 0.5\ CO_p)}\right]$$

$$= (\quad) \times (\quad) \left[\frac{20.9}{20.9 - (\quad - 0.5\ (\quad))}\right]$$

$$= _____ \text{ grains/}10^6 \text{ Btu}$$

PROBLEM IV.3: Calculation of F-factor

F-factors are useful in the calculation of emissions from combustion sources. Consider a bituminous coal having the "as-fired" ultimate analysis of 75% carbon, 5% hydrogen, 6.7% oxygen, 1.5% nitrogen, 2.3% sulfur, 7.0% ash, and 2.5% free moisture. The heating value of this coal is 13,000 Btu/lb.

Calculate:

1. The F-factor, $F_d$, using the Equation 5.2b on p. 5-15 of the Student Manual and compare this value with that given in Attachment 5-5, p. 5-25, of the Student Manual.

Solution to Problem IV.3:

The equation for the F-factor, $F_d$, is

$$F_d = \frac{(3.64\ H_2 + 1.53\ C + 0.57\ S + 0.14\ N - 0.46\ O_2)}{HHV} 10^6 \quad \frac{dscf}{10^6\ Btu}$$

$$= \frac{[3.64\ (\quad) + 1.53\ (\quad) + 0.57\ (\quad) + 0.14\ (\quad) - 0.46\ (\quad)]}{(\quad)}$$

$$= _____ \quad \frac{dscf}{10^6\ Btu}$$

PROBLEM IV.4: Calculation of Pollutant Concentration

Bituminous coal is burned completely at a rate of 5 ton/hr with excess air. An evaluation of the effluent yields the following data:

| | | |
|---|---|---|
| Orsat Analysis: | $CO_2$ | 9.1% |
| | $O_2$ | 10.6% |
| | CO | 0.0% |
| Volume Flow: | 26,000 scfm | |
| Pollutant Mass Rate: | 130,000 grains/min. | |

Compute:

1. The particulate concentration corrected to 50% excess air.
2. The particulate concentration corrected to 12% $CO_2$.
3. The particulate concentration corrected to 6% $O_2$.

Solution to Problem IV.4:

1. Find the particulate concentration, $C_{vs}$, using the flow and the pollutant mass rate from Equation 5.21, p. 5-14 of the Student Manual:

$$C_{vs} = \frac{PMR}{V_s}$$

$$= \frac{(\qquad) \text{ grains/min.}}{(\qquad) \text{ scfm}}$$

$$= _____ \text{ grains/scf}$$

Correct the concentration to 50% excess air using Equations (2) and (3) on p. 5-23 of the Student Manual

$$F_{50v} = 1 - \left[\frac{1.5\ O_{2p} - 0.133\ N_{2p} - 0.75\ CO_p}{0.21}\right]$$

$$= 1 - \left[\frac{1.5\ (\quad) - 0.133\ (\quad) - 0.75\ (\quad)}{0.21}\right]$$

$= 1 - (\quad)$

$= _____$

$$C_{50v} = \frac{C_{vs}}{F_{50_{vs}}} = \frac{(\quad)}{(\quad)}$$

$= _____$ grains/scf at 50% EA

2. Correct the concentration to 12% $CO_2$ using Equations (6) and (7) on p. 5-23 of the Student Manual

$$F_{12v} = \frac{CO_{2p}}{0.12} = \frac{(\quad)}{.12}$$

$= _____$

$$C_{12v} = \frac{C_{vs}}{F_{12}} = \frac{(\quad)}{(\quad)}$$

$= _____$ grains/scf at 12% $CO_2$

3. Correct the concentration to 6% $O_2$ using Equations (10) and (11) on p. 5-24 of the Student Manual

$$F_{6v} = \frac{0.21 - O_{2p}}{0.15} = \frac{0.21 - (\quad)}{0.15}$$

$= _____$

$$C_{6v} = \frac{C_{vs}}{F_{6v}} = \frac{(\quad)}{(\quad)}$$

$= _____$ grains/scf at 6% $O_2$

PROBLEM IV.5: Correction of $NO_X$ Emission Concentration to 3% $O_2$

Limiting the excess air during combustion is an important technique for controlling the $NO_X$ emissions. In order to provide a more meaningful basis for comparison, the resulting emissions will be corrected to a standard basis of 3% $O_2$ (or 3% excess $O_2$). Consider the $NO_X$ emissions of 200 and 300 ppm from an oil-fired power plant under the stack gas conditions A and B, respectively (which have different conditions of excess air).

| Condition | Dry Volume Basis | | | |
|---|---|---|---|---|
| | $CO_2$, % | $O_2$, % | $N_2$, % | $NO_X$, ppm |
| A | 13.3 | 2.2 | 84.5 | 200 |
| B | 9.7 | 7.3 | 83.0 | 300 |

Determine:

1. The excess air corresponding to conditions A and B.
2. The correction factor to be used in correcting $NO_X$ emissions from their actual condition to the basis of 3% $O_2$.
3. The corresponding values of $NO_X$ at the standard basis of 3% oxygen.

Solution to Problem IV.5:

1. Find the excess air for conditions A and B using Equation (1) on p. 5-23 of the Student Manual.

$$\%EA = \left[ \frac{O_{2p} - 0.5\ CO_p}{0.264\ N_2 - (O_{2p} - 0.5\ CO_p)} \right] \times 100\%$$

For condition A:

$$\%EA = \left[ \frac{(\qquad) - 0.5\ (\quad)}{0.264\ (\quad) - (\quad - 0.5\ (\quad))} \right] \times 100\%$$

$$= \underline{\qquad\qquad} \text{ for condition A.}$$

For condition B:

$$\%EA = \left[ \frac{(\quad) - 0.5\,(\quad)}{0.264\,(\quad) - (\quad - 0.5\,(\quad))} \right] \times 100\%$$

= _____ for condition B.

2. The volume correction factor for flue gas $O_2$ is derived from

$$F_{O_2v} = \frac{0.21 - O_{2p}}{0.21 - O_{2\ std}}$$

$$F_{3v} = \frac{0.21 - O_{2p}}{0.21 - 0.03}$$

$$= \frac{0.21 - O_{2p}}{(\quad)}$$

3. Use the correction factor developed above, to correct the measured $NO_X$ emissions at conditions A and B to the 3% $O_2$ standard basis:

For 200 ppm $NO_X$ at _____ % excess air

$$C_{3v} = \frac{C_v}{F_{3v}} = \frac{200\ ppm}{\frac{.21 - (\quad)}{.18}}$$

= _____ ppm corrected to 3% $O_2$

For 300 ppm $NO_X$ at _____ % excess air

$$C_{3v} = \frac{C_v}{F_{3v}} = \frac{\qquad}{\frac{.21 - (\quad)}{.18}} = _____ \text{ ppm corrected to 3\% } O_2$$

CHAPTER V

AFTERBURNER DESIGN PROBLEMS

PROBLEM V.1: Afterburner Design for Meat Smokehouse Effluent

Consider a meat smokehouse discharging 1,000 scfm effluent at 150°F, which needs to be treated to control a very low concentration of pollutants at the parts-per-million level. This could be accomplished by thermal incineration at 1,200°F for at least 0.3 seconds. The following are reasonable assumptions:

1. The amount of combustibles in effluent gases is very low; there is no contribution to the heating value due to their oxidation.

2. Effluent gases have the same thermal properties as air.

3. Intake combustion air is available at 60°F.

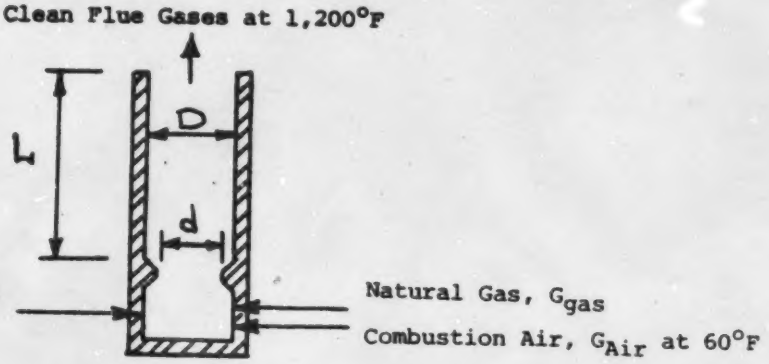
Determine:

1. The natural gas required for preheating the contaminated effluent to 1,200°F using all fresh combustion air intake.

2. The afterburner throat diameter to give 20 ft/sec throat velocity for good mixing.

3. The diameter and the length of the afterburner for a minimum L/D ratio of 2 and afterburner chamber velocity of 12 ft/sec.

Afterburner Schematic:



Solution to Problem V.1:

Choose as a basis for calculation:

1 hour operation

Part 1.

a. Calculate waste effluent flow rate, $\dot{m}$ (lb/hr)

$\dot{m}$ = (volume flow rate) (density)

Since assumed effluent to have properties of air, density from Attachment 2-1, p. 2-23 of the Student Manual.

$\dot{m}$ = (1,000 scfm) (0.0766 lb/scf) (60 min/hr) = 4,600 lb/hr

b. Calculate the heat required to increase the effluent waste stream temperature from 150°F to 1,200°F, allowing for 10% loss (i.e., multiply by 1.10):

$Q = 1.10\ \dot{m}\ \Delta H$

Enthalpy difference, $\Delta H$, obtained by using Attachment 2-7, p. 2-29 of the Student Manual:

| | | |
|---|---|---|
| Enthalpy of air at | 1,200°F is: | 288.5 Btu/lb |
| Enthalpy of air at | 150°F is: | 21.6 Btu/lb |
| Therefore, | $\Delta H$ = | 266.9 Btu/lb |

Therefore,

$Q$ = (1.10) (4,600 lb/hr) (266.9 Btu/lb) = $1.35 \times 10^6$ Btu/hr.

c. Available heat from natural gas, $Q_A$ (Btu/scf)

Assume: Gross heating value of natural gas = 1,059 Btu/scf

Theoretical combustion air = 10.0 scf air/scf gas

Combustion products = 11.0 scf/scf gas.

From Attachment 2-9, p. 2-31 of the Student Manual, obtain for 1,200°F flue gas temperature:

$Q_A$ = 690 Btu/scf

(This is the amount of heat remaining after the combustion products from 1 scf of gas are raised to the afterburner temperature. This heat is then available for heating the waste effluent to the same afterburner temperature.)

d. Natural gas needed, $G_{gas}$ (scfh):

$G_{gas}$ = (1.35 x $10^6$ Btu/hr)/(690 Btu/scf gas) = 1,960 scf gas/hr.

Part 2.

a. Volume of combustion products at 1,200°F, $G_p$ ($ft^3$/sec):

$G_p$ = (1,960 scf gas/hr)(11.0 scf prod/scf gas)(460 + 1,200,°R)/(460 + 60,°R)

= 68,800 $ft^3$/hr = 19.1 $ft^3$/sec.

b. Volume of waste effluent at 1,200°F, $G_E$ ($ft^3$/sec)

$G_E$ = (1,000 scfm)(460 + 1,200,°R)/(460 + 60,°R)

= 3,190 $ft^3$/min = 53.2 $ft^3$/sec.

c. Total volumetric flow of gases to the afterburner chamber through the throat:

$G_{tot}$ = $G_p$ + $G_E$ = 19.1 + 53.2 = 72.3 $ft^3$/sec.

d. Afterburner throat area $A_{throat} = \pi d^2/4$

Throat diameter $d = (4A_{throat}/\pi)^{1/2}$ (A)

Now the velocity through the throat is:

$V_{throat} = G_{tot}/A_{throat}$ (B)

Combining Equations (A) and (B) above to eliminate the throat area and solving for throat diameter, d:

$$d = \left[\frac{4\ G_{tot}}{\pi\ V_{throat}}\right]^{1/2} \quad \text{(C)}$$

For required throat velocity of 20 ft/sec:

$$d = \left[(4/\pi)\ (72.3\ ft^3/sec)\ /\ (20\ ft/sec)\right]^{1/2} = \underline{\underline{2.15\ ft}}$$

Part 3.

Afterburner chamber velocity specified at 12 ft/sec. Thus chamber diameter, D, obtained from Equation (C) above with $V_{throat}$ replaced by $V_{chamber}$ = 12 ft/sec

$$D = \left[(4/\pi)\ (72.3\ ft^3/sec)\ /\ (12\ ft/sec)\right]^{1/2} = \underline{\underline{2.77\ ft}}$$

Length of afterburner chamber ($L/D \geq 2$)

Minimum $L = 2D = (2)\ (2.77) = 5.54$ ft (D)

Check residence time, t

$t = L/V_{chamber} = (5.54\ ft)\ /\ (12\ ft/sec) = 0.46$ sec (E)

Since $t = 0.46$ sec is greater than the minimum required residence time of 0.30 sec, the above design is satisfactory.

Note: Natural gas requirements can be reduced by:

(i) heat recovery from clean gases to preheat incoming waste effluent, and

(ii) using oxygen from the waste effluent stream for combustion, thereby reducing primary air requirements for the auxiliary fuel.

This latter option is illustrated in Problem V.2.

PROBLEM V.2: Afterburner Design with Combustion Oxygen from the Contaminated Effluent

Assume that the meat smokehouse effluent in Problem V.1 has also the same composition as air (21% by volume oxygen) except for the minute concentration of contaminants. Repeat the calculations of Problem V.1, but use the oxygen from the smokehouse effluent for combustion of the auxiliary fuel as much as possible.

Reasonable assumptions are: a mixing-plate type burner (see Attachment 7-6) will be used in this application. A ring baffle, which was used in Problem V.1, will therefore not be necessary to obtain good mixing between the auxiliary fuel combustion products and the effluent to be incinerated.

Determine:

1. The hypothetical available heat for this afterburner application.
2. The natural gas requirements and the fraction of combustion oxygen available from the effluent.
3. The afterburner dimensions as in Problem V.1.

Solution to Problem V.2:

Preliminary Notes on Hypothetical Available Heat Calculations:

Let $X$ = fraction of theoretical air for burning auxiliary fuel entering through the burner (primary or fresh intake air)

$1 - X$ = fraction of theoretical air from waste effluent

$H_E$ = heat content (enthalpy) of effluent at final temperature

$$H_E = C_p \Delta T = (0.24 \text{ Btu/lb-}^{\circ}\text{F})\ (T\text{-}60,\ ^{\circ}\text{F}) \qquad \text{(A)}$$

$W$ = weight of combustion air from effluent

$$W = (A_{Th})\ (1 - X)\ \rho_{Air} \qquad \text{(B)}$$

Heat content, $Q$, of that combustion air at final afterburner temperature

$$Q = W H_E = A_{Th} (1 - X) \rho H_E \quad (C)$$

Since this amount of heat, $Q$, is no longer needed to heat up fresh intake (primary) air, it will be available to heat the rest of the contaminated effluent. Thus we have a "hypothetical" available heat, $Q'_A$:

$$Q'_A = Q_A + Q \quad (D)$$

$$Q'_A = Q_A + A_{Th} (1 - X) \rho H_E \quad (E)$$

where $Q_A$ obtained from sources such as Attachment 2-9, p. 2-31 of the Student Manual

$\rho$ = 0.0766 lb air/scf

$A_{Th}$ = 10.0 scf air/scf natural gas burned (typically)

$H_E$ = calculated from Equation (A)

For a natural gas with 1,059 Btu/scf gross heating value and the above burning characteristics, the hypothetical available heat as a function of the afterburner temperature is:

| Afterburner Temperature °F | Hypothetical Available Heat $Q'_A$, Btu/scf gas |
|---|---|
| 600 | 830 + 100 (1 - X) |
| 800 | 785 + 136 (1 - X) |
| 1,000 | 740 + 173 (1 - X) |
| 1,200 | 690 + 210 (1 - X) |
| 1,400 | 645 + 246 (1 - X) |
| 1,600 | 600 + 283 (1 - X) |
| 1,800 | 550 + 320 (1 - X) |

Part 1.

Assume first that no primary air is needed, i.e. X = 0, and all combustion air comes from the waste effluent. This needs to be checked; if assumption is not justified, adjust value of X and go through the calculations again.

Hypothetical available heat for T = 1,200°F:

$Q'_A$ = _____ + _____ (1 - 0) = _____ Btu/scf gas

Part 2.

Auxiliary natural gas fuel needed

$G_{gas}$ = (Heat to raise effluent to 1,200°F)/$Q'_A$

= ($1.35 \times 10^6$ Btu/hr)/( _____ Btu/scf gas)

= _____ scf gas/hr

Theoretical air needed to burn auxiliary gas:

$G_{air}$ = ($G_{gas}$) ($A_{Th}$)

= ( _____ scf gas/hr) (10.0 scf air/scf gas)/(60 min/hr)

= _____ scfm air.

Compare the above $G_{air}$ with volumetric flow rate of waste effluent (which is equivalent to air).

If $G_{air} < G_{effluent}$, then assumed value of X justified and proceed to next part.

If $G_{air} > G_{effluent}$, then adjust X accordingly and repeat above calculations.

Part 3.

Auxiliary fuel combustion products at 1,200°F, $G'_p$

$$G'_p = (G_{gas} \text{ scf gas/hr})\ (11.0 \text{ scf prod./scf gas})\ (460 + 1200)/(460 + 60)$$

$$= _____ \text{ ft}^3/\text{hr}$$

$$= _____ \text{ ft}^3/\text{sec}$$

Waste effluent volume at 1,200°F, $G'_E$, after removing portion already accounted for in auxiliary fuel burning:

$$G'_E = (1{,}000 - G_{air})\ \left(\frac{460 + _____}{460 +}\right)\ \frac{1 \text{ min}}{60 \text{ sec}} = _____ \text{ ft}^3/\text{sec}$$

Total volumetric flow to afterburner:

$$G'_{tot} = G'_p + G'_E$$

Do Not Film This Page

$$= _____ + _____ = _____ \text{ ft}^3/\text{sec.}$$

Afterburner Chamber Diameter (Equation C from Problem V.1):

$$D = \left[(4/\pi)\ (G'_{tot})\ /\ (12 \text{ ft/sec})\right]^{1/2} = _____ \text{ ft.}$$

Afterburner length:

$$L = 2D = (2)\ (_____) = _____ \text{ ft.}$$

Residence time (Equation (E) from Problem V.1):

$$t = L/V_{chamber} = (_____ \text{ ft})\ /\ (12 \text{ ft/sec}) = _____ \text{ sec}$$

$\geq$ 0.3; hence O.K.

# CHAPTER VI

## COMBUSTION SYSTEM CALCULATIONS

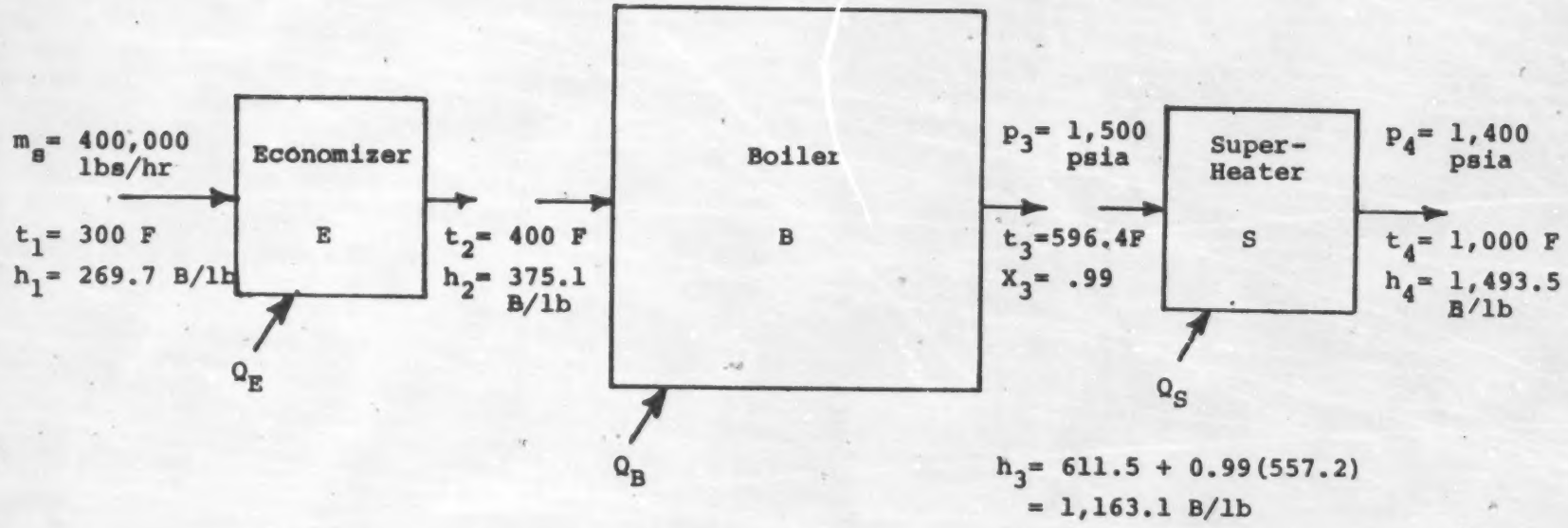
### PROBLEM VI.1: Fuel Requirements for Combustion Installation

A steam generator is rated at 400,000 lbs of steam per hour. Steam (99% dry) leaves the boiler at 1,500 psia pressure and enters a superheater. Steam leaves the superheater at 1,400 psia pressure and a temperature of 1,000°F. The feedwater for this unit enters the economizer at 300°F and leaves at 400°F. The overall thermal efficiency of the steam generator is 74%. The energy and water losses associated with blowdown may be neglected.

Compute:

1. The rate of energy delivered to the:
   (a) economizer,
   (b) boiler,
   (c) superheater, and
   (d) the total delivered
2. The fuel energy required, million Btu/hr
3. The fraction of the fuel energy which is absorbed in the
   (a) economizer,
   (b) boiler, and
   (d) superheater.

SCHEMATIC DIAGRAM FOR PROBLEM VI.1




VI-2

Solution to Problem VI.1:

From the steam tables one may determine the enthalpy values of the feedwater and steam:

| | | | | |
|---|---|---|---|---|
| Economizer inlet: | $t_1$ = 300°F, | | $h_1$ = | 269.7 Btu/lb |
| Economizer exit: | $t_2$ = 400°F, | | $h_2$ = | 375.1 Btu/lb |
| Boiler exit: | $p_3$ = 1,500 psia | | $h_3$ = | 611.5 + X (557.2) |
| | $t_3$ = 596.39°F | | = | 611.5 + .99 (557.2) |
| | X = .99 | | = | 1163.1 Btu/lb |
| Superheater exit: | $p_4$ = 1,400 psia | | $h_4$ = | 1493.5 Btu/lb |
| | $t_4$ = 1,000°F | | | |

1. Compute the energy delivered to each section using Equation 4.13 on p. 4-10 of the Student Manual.

   a. Economizer:

   $$Q_{s_E} = m_s (h_2 - h_1)$$

   $$= 400{,}000 \frac{\text{lb steam}}{\text{hr}} \left( \quad - \quad \right) \frac{\text{Btu}}{\text{lb}}$$

   $$= _____ \text{ Btu/hr}$$

   b. Boiler:

   $$Q_{s_B} = m_s (h_3 - h_2)$$

   $$= 400{,}000 \frac{\text{lb steam}}{\text{hr}} \left( \quad - \quad \right) \frac{\text{Btu}}{\text{lb}}$$

   $$= _____ \text{ Btu/hr}$$

   c. Superheater:

   $$Q_{s_S} = m_s (h_4 - h_3)$$

   $$= 400{,}000 \frac{\text{lb steam}}{\text{hr}} \left( \quad - \quad \right) \frac{\text{Btu}}{\text{hr}}$$

   $$= _____ \text{ Btu/hr}$$

d. Total:

$$Q_{s_T} = Q_{s_E} + Q_{s_B} + Q_{s_S}$$

$$= (\quad) + (\quad) + (\quad) \text{ Btu/hr}$$

$$= _____ \text{ Btu/hr}$$

2. The fuel energy input required may be determined using Equation 4.9 on p. 4-8 of the Student Manual.

$$Q_H = \frac{Q_s}{\eta} = \frac{(\quad) \text{ Btu/hr}}{(\quad)}$$

$$= _____ \text{ Btu/hr}$$

3. The fraction of the fuel energy which is absorbed:

a. Economizer:

$$\frac{Q_{s_E}}{Q_H} = \frac{(\quad)}{(\quad)} = _____ = _____ \%$$

b. Boiler:

$$\frac{Q_{s_B}}{Q_H} = \frac{(\quad)}{(\quad)} = _____ = _____ \%$$

c. Superheater:

$$\frac{Q_{s_S}}{Q_H} = \frac{(\quad)}{(\quad)} = _____ = _____ \%$$

PROBLEM VI.2: Combustion Improvement

Combustion modification of a boiler resulted in changing the excess air as may be determined from the following Orsat analyses of the flue gas:

| Gas | Before Modification | After Modification |
|---|---|---|
| $CO_2$ | 10.1% | 15.0% |
| $O_2$ | 8.3 | 3.1 |
| CO | 0.1 | 0.0 |

The fuel fired was lignite coal which has the following analysis: 0.22% S, 6.39% $H_2$, 37.37% C, 0.61% $N_2$, and 44.99% $O_2$. The heating value is 6,010 Btu/lb and the proximate analysis is: 36.93% moisture, 24.92% volatile matter, 27.72% fixed carbon, and 10.43% ash.

The unit operates 7,700 hr per year with an average load of 5.3 tons of coal per hour with a fuel cost of 75¢ per $10^6$ Btu. Assume that before and after the modification, flue gas temperature was 355°F; the refuse was 0.1062 lb per lb of coal; and the average combustion air was at 75°F.

Compute:

1. The excess air
   (a) before the modification,
   (b) after the modification.
2. The theoretical air required to burn a pound of the specified coal.
3. The theoretical flue gas produced from firing a pound of coal.
4. The actual flue gas produced per pound of coal
   (a) before the modification,
   (b) after the modification.
5. The change in flue gas energy loss per pound of coal.
6. The value of the annual savings from reduced flue gas losses, which occur because of the modification

Solution to Problem VI.2:

1. Compute excess air knowing that:

$$N_2 = 100\% - CO_2\% - O_2\% - CO\%$$

a. Before modification:

$$N_2 = 100\% - (\quad) - (\quad) - (\quad) = _____\ \%$$

Determine %EA from Equation (1), p. 5-23 of the Student Manual:

$$EA = \frac{(\quad) - 0.5\,(\quad)}{0.264\,N_2 - (O_{2p} - 0.5\,CO_p)} \times 100\%$$

$$= \frac{(\quad) - 0.5\,(\quad)}{0.264\,(81.5) - (8.3 - 0.5\,(0.1))} \times 100\%$$

$$= _____\ \%$$

b. After modification:

$$N_2 = 100\% - (\quad) - (\quad) - (\quad)$$

$$= _____\ \%$$

$$EA = \frac{(\quad) - 0.5\,(\quad)}{0.264\,(\quad) - (\quad - 0.5\,(\quad))} \times 100\%$$

$$= _____\ \%$$

2. The theoretical air required is found from Equation 4.1 on p. 4-4 of the Student Manual

$$A_t = 11.53\,C + 34.34\,(H_2 - \frac{O_2}{8}) + 4.29\,S$$

$$= 11.53\,(\quad) + 34.34\,(\quad - \frac{(\quad)}{8}) + 4.29\,(\quad)$$

$$= _____\ \text{lb air/lb coal}$$

3. The theoretical flue gas per pound of coal fired may be obtained from Equation 4.2 on p. 4-5 of the Student Manual, with $m_f = 1$:

$$G = (m_f - \text{noncombustible}) + m_f A_t$$

$$= 1 - (\quad) + 1 (\quad)$$

$$= _____ \text{ lb gas/ lb coal}$$

4a. Before the modification the actual flue gas per pound of coal was

$$G_f = A_g + G$$

$$= EA\ (A_t) + G$$

$$= (\quad) \times (\quad) + (\quad)$$

$$= _____ \text{ lb gas/ lb coal fired}$$

4b. After the modification the actual flue gas was:

$$G_f = (\quad) \times (\quad) + (\quad)$$

$$= _____ \text{ lb gas/ lb coal fired}$$

5. As it was stated that the average ambient and flue gas temperatures did not change after the modification, the difference in flue gas energy loss may be determined using Equation 4.12 on p. 4-8 of the Student Manual

$$\Delta Q_{fg} = (G_{f\ \text{before}} - G_{f\ \text{after}})\ C_p\ (t_{fg} - t_{amb})$$

$$= (\quad - \quad) \times (0.25\ \frac{\text{Btu}}{\text{lb}^{\circ}\text{F}}) \times (\quad - \quad)$$

$$= _____ \text{ Btu/ lb coal fired}$$

6. The value of the annual savings resulting from reduced flue gas losses will be:

$$\text{Annual savings} = \frac{\text{cost}}{\text{Btu}} \times \Delta Q_{fg} \frac{\text{Btu}}{\text{lb coal}} \times m_f \frac{\text{lb coal}}{\text{hr}} \times \text{time} \frac{\text{hr}}{\text{year}}$$

$$= \frac{\$.75}{10^6 \text{ Btu}} \times (\quad) \frac{\text{Btu}}{\text{lb coal}} \times (\quad \times 200) \frac{\text{lb coal}}{\text{hr}}$$

$$\times (\quad) \frac{\text{hr}}{\text{year}}$$

$$= \underline{\$\qquad\qquad} \text{ per year}$$

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**15. SUPPLEMENTARY NOTES**

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**16. ABSTRACT**

This Student Workbook is used in conjunction with Course #427, "Combustion Evaluation" as applied to air pollution control situations. The workbook was prepared by the EPA Air Pollution Training Institute (APTI) to provide problem solving exercises of typical combustion calculations as a supplement to the course lecture materials.

Sample problems are presented for:

- Combustion fundamentals
- Combustion design
- Emission calculations
- Pollutant concentrations
- Afterburner design
- Fuel requirements

Note: There is also an Instructors Guide to be used in conducting the training course (EPA-450/2-80-065) and a Student Manual for reference and additional subject material - (EPA-450/2-80-063)

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